

Fire Evacuation Analysis of High-Rise Buildings Using Path Finder and Fire Dynamics Simulator

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Abstract

Fire evacuation from high-rise buildings is a complex life-safety problem involving fire growth, smoke movement, occupant response, human movement, congestion, and the availability of safe egress routes. Conventional evacuation assessments based only on travel distance or simple hydraulic calculations may not adequately represent the interaction between fire conditions and occupant movement. This study presents a numerical framework for analyzing fire evacuation in a high-rise building using the Fire Dynamics Simulator (FDS) and Pathfinder. FDS is used to simulate fire development, smoke propagation, temperature distribution, visibility, and selected toxic-gas conditions, while Pathfinder is used to model occupant movement, route selection, congestion, travel time, and evacuation performance. The study considers a representative 20-storey high-rise building with two protected staircases and a representative population distributed over the occupied floors. Multiple fire scenarios are proposed, including a low-floor fire, a middle-floor fire, and a high-floor fire. The results framework evaluates pre-evacuation time, total evacuation time, stair congestion, visibility, tenability, and occupant exposure. An illustrative comparison demonstrates that evacuation performance is strongly influenced by fire location, smoke spread, stair availability, occupant distribution, and pre-evacuation delay. The combined FDS–Pathfinder approach provides a more comprehensive assessment than evacuation-only simulation because it enables the evacuation analysis to be interpreted against evolving fire and smoke conditions. The study concludes that high-rise fire safety should be assessed using performance-based evacuation analysis, protected and redundant egress routes, smoke-control measures, occupant preparedness, and scenario-based emergency planning.

Keywords: High-rise building, fire evacuation, Pathfinder, Fire Dynamics Simulator, FDS, smoke movement, evacuation time, occupant movement, visibility, fire safety, egress analysis, tenability.

1. Introduction

Rapid urbanization and increasing population density have resulted in the construction of high-rise residential, commercial, institutional, and mixed-use buildings. These buildings accommodate large numbers of occupants vertically and therefore present significant challenges during fire emergencies. Unlike low-rise structures, high-rise buildings generally require occupants to travel considerable vertical distances before reaching a safe discharge level. Fire, smoke, heat, congestion, impaired visibility, occupant behavior, and delayed decision-making can significantly influence evacuation performance.

The evacuation of occupants during a fire is not simply a matter of identifying the shortest route to an exit. Occupants may initially delay movement because they do not recognize the emergency, may select inappropriate routes, or may encounter congestion in corridors and staircases. Human factors are particularly important in high-rise evacuation.

Research on high-rise evacuation has documented the importance of pre-evacuation behavior, movement speeds, stairwell conditions, crowd density, and route selection.

Computer-based fire and evacuation modelling provides an opportunity to examine these interacting phenomena under controlled scenarios. The Fire Dynamics Simulator (FDS) is a computational fluid dynamics model designed for fire-driven fluid flow and can be used to analyze smoke movement, temperature, visibility, and combustion-related conditions. Pathfinder is an agent-based evacuation simulator capable of representing individual occupants, movement routes, doors, stairs, exits, occupant profiles, and evacuation behavior.

A combined FDS–Pathfinder methodology is particularly useful because fire conditions may change the suitability of evacuation routes over time. Pathfinder can use fire-simulation information to assess occupant exposure to smoke and other hazards. Current Pathfinder documentation also describes integration of FDS results for reduced visibility and Fractional Effective Dose (FED) assessment.

However, it is important to distinguish between *coupled analysis* and simply running two independent programs. The official Pathfinder documentation notes that fully automatic two-way coupling between PyroSim/FDS fire results and Pathfinder evacuation has not historically been completed in the conventional workflow; smoke effects can instead be transferred or incorporated into evacuation modelling using appropriate procedures.

Therefore, the objective of this research is to develop a systematic FDS–Pathfinder methodology for evaluating high-rise fire evacuation and identifying the major parameters affecting evacuation safety.

Objectives

The specific objectives are:

1. To develop a representative high-rise building model for fire evacuation analysis.
2. To simulate fire development and smoke propagation using FDS.
3. To model occupant movement and evacuation routes using Pathfinder.
4. To investigate the influence of fire location on evacuation performance.
5. To determine total evacuation time under different scenarios.

Review of Literature

6.1 High-Rise Fire Evacuation

High-rise evacuation has been investigated extensively because occupant movement differs significantly from conventional low-rise evacuation. The National Research Council Canada has reported observations of evacuation exercises in high-rise office buildings and has emphasized crowd movement, exit stairways, occupant behavior, and emergency procedures as important factors in evacuation design.

Research has also shown that occupant response is not instantaneous. People may initially remain in place due to uncertainty, lack of information, disbelief, or waiting for additional cues before initiating evacuation.

6.2 Occupant Movement

Evacuation time is influenced by population density, walking speed, stair geometry, door widths, merging flows, and behavioral characteristics. Studies involving real evacuation exercises have demonstrated the importance of collecting pre-evacuation time, route choice, movement speed, and arrival time when validating evacuation models.

6.3 Pathfinder

Pathfinder is an agent-based evacuation simulation software that represents occupants as individual agents and allows analysis of their movement through building geometry. The software can model occupant profiles, sources, exits, doors, stairs, and different movement behaviors.

Pathfinder normally directs occupants toward available exits according to the selected movement and behavioral assumptions. It can also support analysis involving fire conditions and integration with FDS/PyroSim outputs.

6.4 Fire Dynamics Simulator

FDS is used to model fire-driven fluid flow and associated thermal and smoke phenomena. For evacuation studies, outputs such as temperature, smoke concentration, visibility, and gas species can be used to determine whether an evacuation route remains tenable.

6.5 FDS–Pathfinder Integration

The combination of fire and evacuation modelling allows evacuation performance to be interpreted within the evolving fire environment. Pathfinder documentation provides procedures for using FDS results to account for reduced visibility and for analyzing occupant exposure.

Current Pathfinder documentation also provides an FED integration procedure based on FDS data. FED can account for occupant exposure to airborne contaminants, including conditions involving carbon monoxide, carbon dioxide, and oxygen concentrations.

Description of the Hypothetical High-Rise Building

For demonstrating the research methodology, a representative 20-storey high-rise building is considered.

Table 1. Building Parameters

Parameter	Assumed Value
Number of floors	20
Floor-to-floor height	3.2 m
Total structural height	Approximately 64 m
Floor plan	40 m × 30 m
Occupancy	Residential/office mixed model
Occupants per typical floor	50
Approximate modeled population 1,000	
Protected staircases	2
Elevator systems	2
Main entrance/exit	Ground floor

Parameter	Assumed Value
Stair width	1.5 m
Typical corridor width	1.8–2.0 m
Fire compartmentation	Assumed
Fire alarm system	Assumed operational

These parameters are examples for methodological demonstration and should be replaced by actual architectural and occupancy data for a real building.

FDS Fire Simulation

The FDS model should include:

- Building geometry
- Walls and floors
- Doors and openings
- Staircases
- Corridors
- Fire source
- Fuel characteristics
- Heat release rate
- Ventilation conditions
- Mechanical smoke-control systems, if present
- Fire suppression systems, if present
- Relevant combustion species
- Output devices

The fire should be defined using an appropriate heat release rate (HRR) curve rather than an arbitrary constant value whenever reliable fire-design information is available.

For a growing fire, the commonly used t-squared representation is:

$$\begin{aligned} &[\\ &Q(t)=\alpha t^2 \\ &] \end{aligned}$$

where:

- $Q(t)$ = heat release rate at time (t)
- (α) = fire growth coefficient
- (t) = time after ignition.

The FDS simulation should generate time-dependent information on:

- Temperature
- Smoke concentration

- Visibility
- Carbon monoxide
- Carbon dioxide
- Oxygen concentration
- Heat flux
- Smoke layer development
- Fire growth
- Flow through openings

Smoke and Visibility Analysis

Visibility is an important factor affecting evacuation. As smoke concentration increases, visibility may decrease and occupant movement may become slower.

The simulation should identify:

1. Time at which smoke reaches each floor.
2. Time at which visibility becomes critically reduced.
3. Smoke conditions in staircases.
4. Smoke conditions in corridors.
5. Temperature at occupant height.
6. Toxic-gas concentrations.
7. Duration for which each route remains usable.

A major benefit of the FDS simulation is that evacuation routes can be evaluated as **time-dependent environments**, rather than being assumed safe for the entire evacuation period.

Pathfinder Evacuation Model

The Pathfinder model should reproduce the building geometry required for occupant movement.

The following parameters should be defined:

- Occupant population
- Occupant location
- Occupant size
- Walking speed
- Pre-evacuation time
- Stair movement
- Door characteristics
- Exit locations
- Route-selection behavior
- Occupant distribution
- Mobility characteristics
- Response delays.

Pathfinder's agent-based approach permits individual occupants to be represented separately and allows the model to examine route selection and congestion.

Occupant Distribution

For the illustrative model, 50 occupants per floor are assumed.

Therefore:

$$[\\ N=20\\times50=1000 \\]$$

where:

- (N) = total modeled occupants.

In an actual study, population should be derived from the building's occupancy classification, floor area, operating conditions, and applicable building/fire-safety requirements.

Pre-Evacuation Time

Pre-evacuation time consists of:

$$[\\ T_{\{pre\}}=T_{\{detection\}}+T_{\{alarm\}}+T_{\{recognition\}}+T_{\{response\}} \\]$$

where:

- $(T_{\{detection\}})$ = fire detection delay,
- $(T_{\{alarm\}})$ = alarm notification delay,
- $(T_{\{recognition\}})$ = time required for occupants to understand the emergency,
- $(T_{\{response\}})$ = time before movement begins.

This parameter should not be treated as zero in realistic evacuation modelling because human response is an important component of actual evacuation behavior. Research involving real evacuation exercises has demonstrated that occupants may exhibit substantial delays before initiating movement.

Total Evacuation Time

The overall evacuation time can be expressed conceptually as:

$$[\\ T_{\{evac\}}=T_{\{pre\}}+T_{\{travel\}}+T_{\{queue\}}+T_{\{exit\}} \\]$$

where:

- $(T_{\{pre\}})$ = pre-evacuation time,
- $(T_{\{travel\}})$ = travel time,
- $(T_{\{queue\}})$ = congestion/queuing time,
- $(T_{\{exit\}})$ = final exit/discharge time.

This decomposition helps identify the major contributor to evacuation delay.

Integration of FDS and Pathfinder

The integrated approach consists of the following sequence:

Step 1

Develop the high-rise geometry.

Step 2

Define the fire source and fire growth characteristics in FDS.

Step 3

Run the fire simulation.

Step 4

Extract smoke, visibility, temperature, and gas-related information.

Step 5

Identify floors and routes affected by smoke.

Step 6

Construct the corresponding Pathfinder evacuation model.

Step 7

Assign occupants to floors and rooms.

Step 8

Define evacuation routes and alternative exits.

Step 9

Apply appropriate movement restrictions or speed modifiers based on fire conditions.

Step 10

Run the evacuation simulation.

Step 11

Compare evacuation time with the development of hazardous conditions.

Step 12

Assess whether occupants reach safe locations before unacceptable fire conditions are encountered.

The official Pathfinder documentation describes a procedure in which FDS-derived visibility information can be used to modify occupant walking speed and route behavior.

Illustrative Simulation Results

Important: The following values are illustrative and are not claimed to be outputs from an actual FDS or Pathfinder run.

Table 2. Illustrative Results for Fire Scenarios

Scenario	Fire Floor	Staircases Available	Illustrative Time	Evacuation	Major Observation
S1	5th	2	18.5 min		Significant lower-floor flow and stair congestion
S2	10th	2	20.2 min		Greater interaction between upper/lower occupant flows
S3	17th	2	22.1 min		Longer travel distance for upper floors
S4	10th	1	29.4 min		Severe congestion in remaining staircase

These values are intended solely to demonstrate how results can be reported.

The illustrative results indicate that evacuation time increases as the fire location changes and as the availability of egress routes decreases. The single-staircase condition produces the largest evacuation delay because a substantial number of occupants are forced to use the same vertical egress route.

Effect of Staircase Availability

The availability of multiple independent evacuation routes is particularly important in high-rise buildings.

In the two-staircase condition, occupants can distribute themselves between the available routes. When one staircase becomes unavailable, the remaining staircase becomes a bottleneck.

A conceptual relationship can be expressed as:

$$C_{\text{stair}} = \frac{N_{\text{occupants}}}{W_{\text{eff}}}$$

where (C_{stair}) represents the relative congestion tendency and (W_{eff}) represents effective available egress width.

The equation is conceptual rather than a complete stair-flow design equation; actual capacity calculations should follow the applicable fire and building-code methodology.

Smoke-Dependent Evacuation

A major advantage of integrating FDS and Pathfinder is the ability to examine evacuation in relation to changing smoke conditions.

For example, consider an evacuation route with initially acceptable visibility. If FDS predicts progressive smoke accumulation, the corresponding Pathfinder simulation may incorporate reduced walking speed or route redirection.

The relationship can be conceptually represented as:

$$\begin{bmatrix} V_{\text{walk}} = V_0 \times f(\text{VIS}) \end{bmatrix}$$

where:

- (V_{walk}) = smoke-affected walking speed,
- (V_0) = normal walking speed,
- $(f(\text{VIS}))$ = visibility-dependent speed factor.

Pathfinder's published tutorial demonstrates the use of visibility-derived speed factors to represent smoke effects on occupant movement.

Discussion

The proposed FDS–Pathfinder framework demonstrates that evacuation performance depends on the interaction between building geometry, fire development, smoke spread, occupant characteristics, and egress capacity.

The first important observation is that **fire location matters**. A fire on a lower floor may affect occupants descending from a large number of upper floors, while a fire on an upper floor can increase travel distances and potentially expose occupants near the fire origin.

The second important factor is **staircase availability**. Multiple independent protected staircases provide route redundancy. When one route becomes unavailable, occupants are redirected to the remaining route and congestion can increase significantly.

The third factor is **pre-evacuation behavior**. Evacuation simulation that assumes instantaneous response may underestimate actual evacuation requirements. Human factors research has identified recognition, decision-making, route choice, and stairwell behavior as important components of high-rise evacuation.

The fourth factor is **smoke propagation**. A route that is physically available may not remain safe throughout the entire evacuation period. This is why FDS-based fire conditions should be examined alongside Pathfinder occupant trajectories.

The fifth factor is **occupant diversity**. Real buildings include occupants with different walking speeds, ages, physical capabilities, familiarity with the building, and emergency responses. Future models should therefore incorporate multiple occupant profiles rather than a single homogeneous population.

Recommendations for High-Rise Fire Safety

Based on the research framework, the following measures are recommended:

Provide Redundant Protected Staircases

High-rise buildings should provide multiple independent protected egress routes so that the loss of one route does not eliminate evacuation capacity.

Improve Smoke Control

Smoke-control systems should be designed, maintained, and tested to reduce smoke migration into escape routes.

Conduct Scenario-Based Evacuation Analysis

Evacuation assessment should consider multiple fire locations rather than a single design fire.

Reduce Pre-Evacuation Delay

Regular fire drills, alarm awareness programs, emergency signage, and occupant training can reduce recognition and response delays.

Conclusion

This research presents a systematic framework for the fire evacuation analysis of high-rise buildings using Fire Dynamics Simulator and Pathfinder. FDS can be used to investigate fire development, smoke movement, temperature, visibility, and relevant fire-effluent conditions, whereas Pathfinder can be used to simulate occupant movement, route selection, congestion, and evacuation time.

The principal advantage of the combined methodology is that it considers evacuation as a dynamic process occurring within a changing fire environment. An evacuation route cannot be considered safe solely because it is geometrically available; its suitability may change as smoke and heat propagate through the building.

The analysis indicates that fire location, staircase availability, occupant population, pre-evacuation delay, route congestion, and smoke conditions are key factors affecting high-rise evacuation performance. The use of multiple protected evacuation routes and effective smoke-control measures can improve evacuation resilience.

For academic and professional applications, the proposed methodology can support performance-based fire-safety design, emergency planning, evacuation strategy development, and identification of high-risk building areas. However, the illustrative results in this paper must be replaced with actual FDS and Pathfinder outputs before the work is presented as an empirical simulation study.

Overall, **FDS–Pathfinder integrated modelling provides a valuable computational framework for evaluating the interaction between fire development and human evacuation in high-rise buildings.**

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